CHEMICAL ENGINEERING TRANSACTIONS

VOL. 26, 2012

Guest Editors: Valerio Cozzani, Eddy De Rademaeker

**ISBN** 978-88-95608-17-4; **ISSN** 1974-9791

A publication of AIDIC

The Italian Association of Chemical Engineering

Online at: www.aidic.it/cet

DOI: 10.3303/CET1226101

# Risk Assessment of Past Exposure in Forensic Engineering

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For the reconstruction of past exposures are often not available measures or, when available, they are inaccurate and do not cover the entire period of interest; the reliability of the measures is a crucial point because in a working environment the concentration of a pollutant is not uniform and is not constant in time. Starting from a suitable set of measures carried out in a given period inside an existing plant, it is possible to estimate past exposures by applying a simple model that takes into account three fundamental parameters: process productivity, protection and mitigation systems and technology in use. The proposed methodology has been applied to a case-study; in particular an industrial process for the production of carbon-based electrodes has been analyzed and the workers exposure to PAH has been considered. A good agreement between experimental measures and model predictions has been evidenced, thus confirming the feasibility and effectiveness of this methodology.

## 1. Introduction

In legal litigations concerning diseases with long latency (i.e. of few decades such as the case of asbestos) to demonstrate the causal relationship it is required a reconstruction of past exposures (Chen et al., 2012; Sahmel et al., 2010). In order to attribute a given cause to an observed effect, in fact, an epidemiological investigation is not enough even though its issues highlight a higher incidence of the considered disease than in general population (Plato et al. 1997; van Tongeren et al. 1998).
The presence of a substance in the workplace and its concentration (Cherrie, 1999) can be briefly described through a material balance. Considering a generic environment (Figure 1) where there are one or more sources of pollution (S) with a generation flow-rate (G), a ventilation flow-rate (Q) with pollutant concentration (Ce) which removes an equal amount of polluted air; if the environment can be considered perfectly mixed, the concentration in the environment (C) will be equal to the outlet concentration. In real environments, however, the concentration is not uniform being variable in time and space; moreover, the average concentration will depend on the mixing efficiency promoted by the ventilation system, Er. As a result of this observation, the exposure of individual workers will depend on the periods they spent in a particular workplace and on the pollutant concentration at that time (Burdorf and van Tongeren, 2003; He et al., 2009).

## 2. Methodological approach

Starting from the previous assumptions, for the individual worker *j*, his exposure can be expressed as:

$$\overline{C_j} = \frac{\sum_j \left(C_{vs,j} \cdot t_{vs,j} + C_{ls,j} \cdot t_{ls,j}\right)}{\sum_i \left(t_{vs,j} + t_{ls,j}\right)} \tag{1}$$

Please cite this article as: Nano G., Derudi M. and Rota R., 2012, Risk assessment of past exposure in forensic engineering, Chemical Engineering Transactions, 26, 603-608 DOI: 10.3303/CET1226101

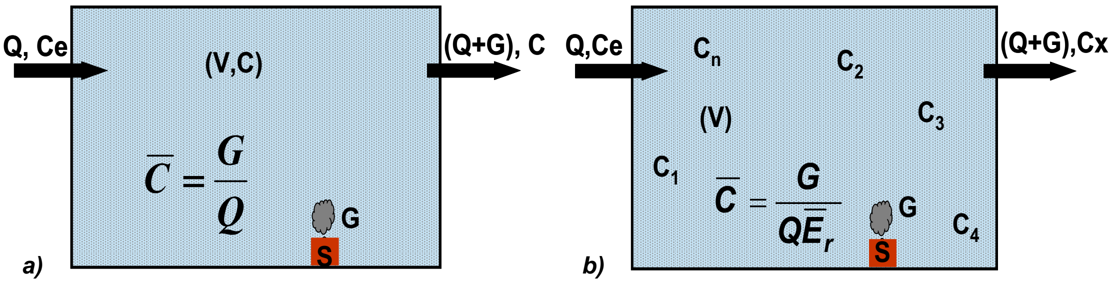


*Figure 1: Representation of the pollutant concentration in a workplace for a well-mixed (a) or a less efficiently ventilated (b) environment*

where: $C_{vs}$ = pollutant concentration close to the source for the different working phases, $C_{ls}$ = pollutant concentration far from the source and $t$ = period of actual exposure to a given pollutant concentration.
Considering all the workers of a specific workplace, it is then possible to evaluate the exposure of the *j*-th worker in a generic day *i* as:

$$\bar{C}_{ij} = \mu \pm \beta_j \pm \varepsilon_{ij} \tag{2}$$

with: $C_{ij}$: exposure of the *j*-th worker for the day *i*; $\mu$: average value of the exposure for the entire group of workers; $\beta_j$: deviation of the *j*-th worker exposure from the group average value; $\varepsilon_{ij}$: deviation from the *j*-th worker average exposure during the day *i*. This relationship takes into account both space and time variability of the exposure of individual workers, as well as differences in exposures between worker and worker (Nano, 2010).
Being unable to measure the exposure of each individual worker, the proposed methodology proceeds to determine the average concentration for a given group of workers, whose value could be reasonably used to characterize all the workers of such a group (Burdorf, 1993; Kromhout et al., 1987). To minimize the difference between the average value of the group and the average value at which an individual workers is exposed it is necessary to minimize the value of $\beta_j$ performing an accurate analysis of plant, process and working procedures to identify a homogeneous risk group of workers, whose average exposure level becomes, with a predefined uncertainty, representative of all the workers of this group (Peretz et al., 2002; Rappaport et al., 1999).
By performing a random sampling on a sufficient number of workers it is possible to estimate from day to day the variability of the exposures representative of the group. In the literature there are several statistical methods for the definition of the sample size. To define the exposure of *N* workers belonging to a group, the NIOSH (National Institute for Occupational Safety and Health) proposes to randomly choose *n* workers depending on the level of confidence *(1 - $\alpha$)* chosen by the analyst and the percentage of workers $\theta$ that it is believed to have an exposure higher than the others, using the following expression (Leidel et al., 1977):

$$\alpha = \frac{[(1-\theta)\cdot N]!}{[(1-\theta)\cdot N - n]!} \cdot \frac{[N-n]!}{[N]!} \tag{3}$$

Once the group is identified and the measurements are performed it is possible to verify the correctness of the data grouping procedure by using common statistical tests; a simple method (though not accurate) requires to plot the measured values as a function of a cumulative probability, as shown in Figure 2; if the measures belong to the same group, log transformed data should lay along a straight line, thus identifying an homogeneous group of workers with a similar exposure profile.
Consequently, the past homogeneous risk exposure can be estimated through a suitable set of measures carried out in an existing plant. By planning and performing measures which meet the requirements for the minimization of the previously discussed errors, it is possible to estimate past exposures by applying a simple model that takes into account three fundamental parameters: process productivity (index of the source term), presence of protection and mitigation systems (index of

possible pollutant dispersion and/or removal) and production technology in use (index of worker exposure scenario) (Plato et al., 1995; Cherrie and Schneider, 1999).

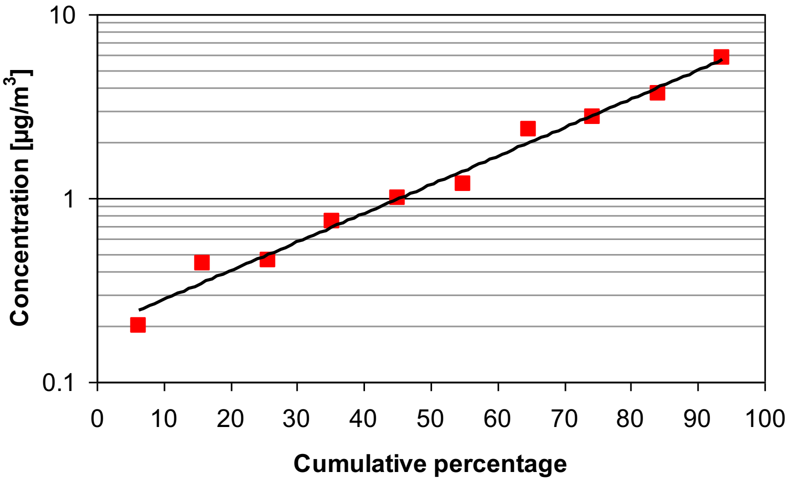


*Figure 2: Example of concentration measures which exhibit the trend of a typical homogeneous group of workers*

Since the three terms are independent, the overall effect is obtained by multiplying together the corresponding coefficients. As an example, increasing the generation term (that means increasing the production) without modifying other parameters, the pollutant concentration will increase proportionally. With this model, once obtained a set of measures made in a given year, the average concentration in the same workplace can be estimated for past years, in which the above mentioned parameters were different, as follows:

$$C_{past} = C_0 \cdot \prod_j \mu_{j,past} \tag{4}$$

where $C_{past}$: estimated concentration related to a past period, $C_0$: measured concentration related to a given period, $\mu_{j,past}$: score of the *j*-th parameter related to the estimation period. A fundamental requirement for the application of such a methodology is the need of a set of measures obtained with accuracy so as to minimize problems arising from the representativeness of the group, the differences within the grouped data and the measurement uncertainties. Only in this way it is possible to estimate a reliable current exposure ($C_0$), that is a paramount parameter for the past exposure estimation.
Then, from a historical reconstruction of the measures introduced in the workplace the concentration is weighted by means of dimensionless coefficients according to the scheme shown in Table 1. For the quantification of the scores it is needed a detailed survey of both plant and process changes made in the past; this should be carefully studied. Another important parameter is the use of personal protective equipments which, in a conservative approach, it is not generally taken into account. The combination of the handicap coefficients is finally used to estimate past concentrations in the workplace.

*Table 1: estimation of the handicap coefficients*

| Period | Parameters | | | |
|---|---|---|---|---|
| | Productivity | Technology | Mitigation (ventilation) | $\prod_j \mu_j$ |
| Current year (year 0) | 1 | 1 | 1 | 1 |
| year -1 | $\mu_{1,-1}$ | $\mu_{2,-1}$ | $\mu_{3,-1}$ | $(\mu_{1,-1}) \cdot (\mu_{2,-1}) \cdot (\mu_{3,-1})$ |
| year –x | $\mu_{1,-x}$ | $\mu_{2,-x}$ | $\mu_{3,-x}$ | $(\mu_{1,-x}) \cdot (\mu_{2,-x}) \cdot (\mu_{3,-x})$ |

Sometimes, for past years, environmental measures are available but it is unknown how these data have been collected; often these measures have been made using methods that were unable to minimize intergroup differences. So, it is clear that these data cannot ensure a reconstruction of the past exposure in the same way it can be done using the previously discussed methods. However, such measures may be fairly good estimators of the exposure magnitude and may be used, at the end, to test the predictive capabilities of the used model.

## 3. Case-study analysis and discussion

The above method has been applied for the estimation of past exposures to polycyclic aromatic hydrocarbons (PAHs), that are classified R45 (carcinogenic) by the European Community; in particular, as a case-study, an industrial process for the production of big carbon-based electrodes has been analyzed.

For the electrodes production, graphite and charcoal are crushed and sieved to obtain the required particle size, then the powder is fed to the mixers and mixed with liquid coal tar. The paste thus obtained is introduced into the extrusion press to form the products. Once cooled these carbon artefacts are sent to the baking and graphitizing phases where, at temperatures between 700 and 1200 °C, they reach the desired mechanical, physical and chemical properties. The presence of polycyclic aromatic hydrocarbons (PAHs) in the ambient air comes from both the use of the liquid coal tars, that are kept at 200 °C to reduce their viscosity, and the fact that the processes are carried out at intermediate or high temperatures.

For the estimation of past exposure a sampling campaign has been planned on the basis of a classification of the workers. They have been divided into groups characterized by similar exposure profiles (Corn and Esmen, 1979); in particular, more than 80 personal samples and 50 environmental measures have been collected. For the definition of the handicap coefficients, the procedure was to assign the coefficients of the three above mentioned parameters without knowing the measures already available for previous years; then, these parameters have been coupled with the concentrations measured for the year 0 (represented by a triangle in the following figures) in order to estimate the past exposure trends. The available historical data were subsequently superimposed to the plots (empty symbols in the following figures) to verify the reliability of the predicted trends.

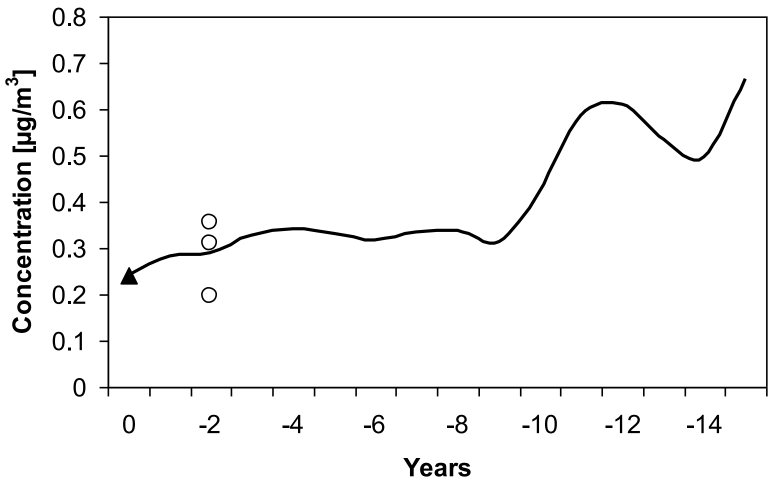


*Figure 3: Comparison among measured PAHs concentrations and predicted trends (blending area)*

Results predicted by means of the model (solid lines), performed for the past 15 years, in three different areas of the plant that are commonly affected by the presence of the carcinogenic PAHs, are reported in Figures 3, 4 and 5. As it is possible to notice, current year measures (year 0) are often lower than the concentrations estimated for past periods because mitigation and protection actions were carried out only in the last few years; moreover, the fact that estimated concentrations sometimes show rise and decay trends is due to a change in the productivity coefficient.

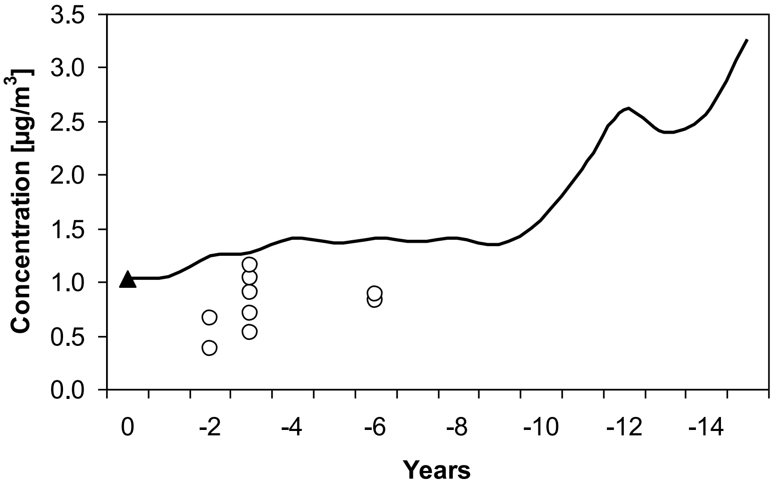


*Figure 4: Comparison among measured PAHs concentrations and predicted trends (extrusion area)*

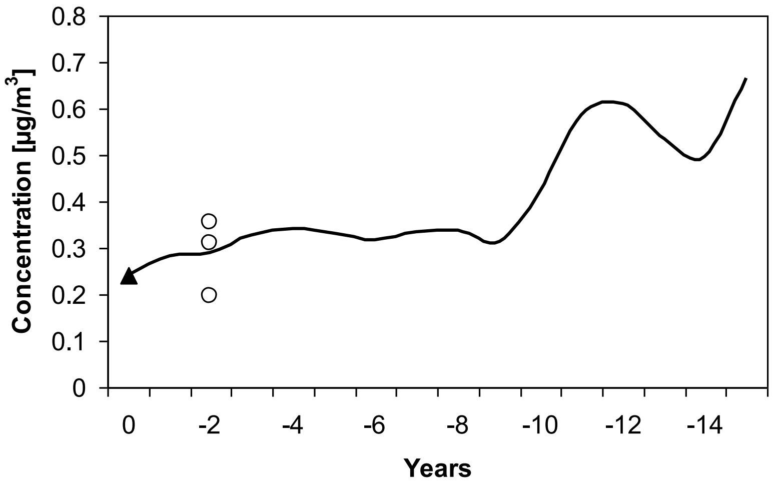


*Figure 5: Comparison among measured PAHs concentrations and predicted trends (baking area)*

About the historical data (empty symbols) the sampling strategy and the procedures adopted by the analysts are unknown; it is only possible to say that past measures have not been obtained by a method as accurate as that used for the year 0 sampling campaign. Nevertheless, model predictions (obtained independently) and measured values are always of the same order of magnitude and the predicted profiles fairly reproduce the trends of the measured concentrations.

## 4. Conclusions

The proposed methodology has been applied to study an industrial process for the production of carbon-based electrodes; the workers exposure to PAHs has been considered. A good agreement between independent experimental measures, carried out by a national agency, and model predictions has been evidenced over the years, thus confirming the feasibility and effectiveness of this methodology.

In particular, it is interesting to notice that in the extrusion area, in which a considerable number of independent measurements were made in different years, not only the proposed model is able to fairly estimate the real concentrations but also their trend as a function of the time.

The study, carried out for a legal litigation, evidenced that the PAHs concentration in the past years was always largely below the levels that can be considered for the risk of exposure of the workers. A confirmation of such a low level has been obtained also from a recent epidemiological survey, based on the analysis of about 1100 workers that were employed in different periods starting from 1950 in this enterprise, that showed no excess diseases related to an exposure to PAHs.

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